Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.VI)

**10-1-13**

# NONLINEAR RESPONSE OF CONCRETE GRAVITY DAMS

Luis M. VARGAS-LOLI[1] and Gregory L. FENVES[2]

[1]Department of Civil Engineering, The University of Texas at Austin, Austin, Texas, U.S.A.
[2]Department of Civil Engineering, University of California, Berkeley, California, U.S.A.

## SUMMARY

The earthquake response of a typical concrete gravity dam-water system is studied to assess the importance of cavitation in the impounded water. The results indicate that water cavitation has little influence on the maximum displacement and stresses in dams. Cavitation increases the maximum acceleration at the dam crest. The amplified accelerations may affect the response of stiff appurtenant equipment or the stability of the upper portion of a dam after extensive cracking of the concrete.

## INTRODUCTION

Linear dynamic analysis provides important information on the earthquake response of concrete gravity dams, in particular the significance of dam-water interaction and water compressibility. However, the realistic dynamic analysis of dams should include the effects of various nonlinearities in the response to earthquake ground motion. One nonlinear effect is cavitation, the formation of gaseous regions in the water that occur when the dam acceleration is large enough for the absolute pressure in the water to reach the vapor pressure.

Early studies of water cavitation and concrete gravity dams used simplifying assumptions of a rigid dam and incompressible water. In such cases, the ground acceleration needed to produce water cavitation in a full reservoir is inversely proportional to the square root of the dam height (Ref. 2). This criterion does not apply to flexible dams impounding a compressible fluid because the acceleration along the dam height depends on the vibration properties of the dam-water system and the ground motion. Previous investigations of cavitation effects on the earthquake response of concrete gravity dams are limited and with differences in conclusions (Refs. 2 and 5).

In this study, a typical concrete gravity dam is analyzed to determine the significance of water cavitation on the response to earthquake ground motion. The complete dam-water system is modeled including water compressibility.

## ANALYSIS PROCEDURE

A numerical procedure for computing the nonlinear dynamic response of fluid-structure systems (Ref. 3) is applied to a two-dimensional model of a concrete gravity dam impounding a reservoir of compressible water. The water is idealized as an inviscid fluid undergoing small amplitude, irrotational motion. The equation of state for water represents the effects of cavitation by a bi-linear pressure-density relationship (Ref. 1). The water is linearly compressible for pressures greater than the vapor pressure, but the water can expand at the constant vapor pressure. The equation of state is shown in Fig. 1 in terms of hydrodynamic pressure and change in density, where c is the velocity of wave propagation, $p_v$ is the vapor pressure, and $p_0$ is the hydrostatic pressure.

The semi-infinite extent of water in the upstream direction is modeled by a finite fluid domain with an approximate radiating boundary condition at the upstream end. Sediments deposited at the reservoir bottom are represented by an absorbing boundary condition. Linear surface waves at the free surface are allowed, although they have a small effect on the earthquake response of dams.

The dynamic analysis procedure uses a displacement finite element formulation for the structure and a mixed pressure-displacement formulation for the fluid. Enforcing equilibrium and normal compatibility at the fluid-structure interface results in coupled, symmetric, nonlinear equations of motion for the fluid-structure system (Ref. 3):

$$\mathbf{M}\ddot{\mathbf{X}} + \mathbf{C}\dot{\mathbf{X}} + \mathbf{K}\mathbf{X} + \mathbf{F} = -\mathbf{M}\mathbf{R}\ddot{\mathbf{u}}_g - \mathbf{C}_F\mathbf{R}\dot{\mathbf{u}}_g - \mathbf{K}_F\mathbf{u}_g \tag{1}$$

where **X** is the vector of nodal displacements in the structure and fluid; **M**, C, and **F**=**F**(**X**) are the mass, damping, and vector of nonlinear restoring forces for the coupled system, respectively; and **K** is the stiffness matrix required to constrain irrotational motion in the fluid. The right-hand side of Eq. (1) is the dynamic force due to the ground motion, $\mathbf{u}_g$, in which **R** is the influence matrix for the ground motion components, $\mathbf{C}_F$ is a matrix that represents radiation of waves at the truncated fluid boundary, and $\mathbf{K}_F$ accounts for linear surface waves at the free surface.

In a typical two-dimensional analysis four node non-conforming elements are used for the structure and four node constant pressure elements are used for the fluid. The equations of motion are solved in the time domain using an implicit time integration procedure with equilibrium iterations based on the Newton-Raphson method. Time steps of 0.02 sec and 0.01 sec for dams with linear fluid and cavitating fluid, respectively, were found adequate for accurate response.

Material nonlinearities in the dam, such as tensile cracking of concrete, can be included in the analysis procedure. The effects of concrete tensile cracking on the earthquake response of dams are not presented here, although they are available in Ref. 4.

## SYSTEM CONSIDERED

The tallest, nonoverflow monolith of Pine Flat dam is taken as a typical example of a concrete gravity dam to study water cavitation. The finite element model of the dam-water system is shown in Fig. 2, in which the upstream length of the reservoir is three times the dam height of 400 ft and the water depth is 381 ft. For showing the earthquake response, Point 1 is on the upstream side of the dam crest and point A is in the water at a depth of 34.5 ft. Positive displacements and accelerations are in the upstream direction.

The concrete in the dam is assumed homogeneous, isotropic, and linear elastic, with the following properties: elastic modulus, $3.25 \times 10^6$ psi; Poisson ratio, 0.20; and unit weight, 155 $lb/ft^3$. Assumed stiffness proportional damping provides five percent of critical damping at the fundamental vibration frequency of the dam alone. The water has the following properties: velocity of wave propagation, 4720 ft/sec; unit weight, 62.4 $lb/ft^3$; and vapor pressure, measured with respect to atmospheric pressure, -15 $lb/in^2$.

Two earthquake ground motions, Taft Lincoln School Tunnel (1952 Kern County) and Pacoima dam (1971 San Fernando), are selected for evaluation of cavitation effects. The S69E horizontal component of the Taft ground motion is scaled from a peak ground acceleration of 0.18 g to 1.0 g to induce cavitation in the water. The S16E horizontal component of the Pacoima ground motion, with a peak ground acceleration of 1.17 g, is not scaled.

## RESPONSE RESULTS

The response of the 400 ft. dam-water system due to the S69E horizontal component of the Taft ground motion is shown in Fig. 4. The hydrodynamic pressure at Point A, as shown in Fig. 4(a), demonstrates that the water will not sustain a pressure less than the vapor pressure with the bilinear equation of state. Cavitation initiates at 3.95 sec when the dam is displaced in the upstream direction. The acceleration in the downstream direction produces a cutoff in hydrodynamic force on the upstream face of the dam. One-half cycle of vibration later, as the velocity of the dam decreases from the maximum value, the cavitated region collapses, producing a pressure pulse of high amplitude and short duration. The pressure pulse, caused by impact of the water as the cavitated region collapses, subsequently produces a large amount of additional cavitation. Fig. 3(b) shows the count of cavitation events in the fluid elements during the ground motion, where the intensity of the shading in the fluid elements is proportional to the number of times the absolute pressure in the element reaches the vapor pressure. The amount of cavitation decreases with depth because the hydrostatic pressure increases with depth; cavitation decreases in the upstream direction because the hydrodynamic pressure decreases exponentially in the upstream direction.

Although there is severe cavitation in the water, Fig. 4(b) reveals that the effect on the maximum dam displacement is very small. The cutoff of hydrodynamic force in the upstream direction slightly reduces later displacement peaks. The maximum principal stresses at several locations in the dam are shown in Fig. 3(a) with and without cavitation. The maximum stresses occur near geometric discontinuities in the cross section. As with displacements, cavitation has a very small effect on stresses. The maximum principal stresses exceed the tensile strength of concrete, indicating that tensile cracking is a more important nonlinear effect in concrete dams.

Cavitation has a major effect on the acceleration of the dam crest. Fig. 4(c) shows the maximum crest acceleration is 2.5 g for the linear fluid, whereas the crest acceleration, more than doubles to 5.5 g for the cavitating fluid. The peak acceleration occurs at the same time (8.2 sec) as the largest pressure pulse from cavitation collapse.

The response of the 400 ft dam-water system to the S16E horizontal component of the Pacoima ground motion is shown in Fig. 5. Compared to the scaled Taft ground motion, the Pacoima ground motion produces less cavitation even though the peak ground acceleration is greater. The observations on the small effect of cavitation on the displacement and stresses in the dam are the same as noted for the Taft ground motion. As before, the increase in peak acceleration at the crest due to cavitation of the water is significant.

To investigate the effect of dam height on cavitation, a 600 ft high dam-water system was obtained by uniformly scaling the finite element model in Fig. 2. Less cavitation occurs when the taller dam is subjected to the Taft ground motion, and no cavitation occurs when subjected to the Pacoima ground motion. The reduction in cavitation with increasing dam height contradicts the conclusion for rigid dams. The reduction in cavitation results from a decrease in the response spectrum ordinate for the two ground motions as the period of the dam-water system lengthens with height.

More extensive results are given in Ref. 4, including the effects of reservoir bottom absorption and the response to vertical ground motion.

## SUMMARY AND CONCLUSIONS

The level of earthquake ground motion that produces cavitation in water impounded by a concrete gravity dam generally produces tensile stresses in the dam that exceed the tensile strength of concrete. When cavitation of the water occurs, it has little effect on the maximum displacements and stresses in dams because the reduction in hydrodynamic force in the upstream direction is small compared to the inertial and elastic forces. The large pressure pulses that result from cavitation collapse do not affect the displacement and stresses in the dam. However, the pressure pulses can significantly amplify the peak accelerations of the dam because (1) the pulses are resisted by dam inertia, and (2) the acceleration of the upstream face is proportional to the large pressure gradients that develop in the water.

The amplified accelerations from water cavitation may affect the response of stiff appurtenant equipment attached to a dam crest. Also, if the upper portion of a dam cracks extensively during an earthquake, the amplified accelerations may reduce post-cracking stability of the dam.

## ACKNOWLEDGEMENTS

The National Science Foundation supported this work under Grant ECE-850449 to The University of Texas at Austin. The Center for High Performance Computing, The University of Texas, allocated time on the Cray X-MP/24 for the computations.

## REFERENCES

1. Bleich, H.H., and Sandler, I.S., "Interaction Between Structures and Bilinear Fluids," Inter. Jour. Solids and Struct., 6, 617-639, (1970).

2. Clough, R.W., and Chang, C.H., "Seismic Cavitation Effects on Gravity Reservoirs," Numerical Methods in Coupled Systems, R.W. Lewis, et al, eds., John Wiley, (1984).

3. Fenves, G., and Vargas-Loli, L.M., "Nonlinear Dynamic Analysis of Fluid-Structure Systems," Jour. Eng. Mechanics, ASCE, 114, 219-240, (1988).

4. Vargas-Loli, L.M., and Fenves, G., "Nonlinear Earthquake Response of Concrete Gravity Dams," Report to NSF, Depart. of Civil Eng., The University of Texas at Austin, (1987).

5. Zienkiewicz, O.C., Paul, D.K., and Hinton, E., "Cavitation in Fluid-Structure Response (with Particular Reference to Dams Under Earthquake Loading)," Earthquake Eng. and Struct. Dynamics, 11, 463-481, (1983).

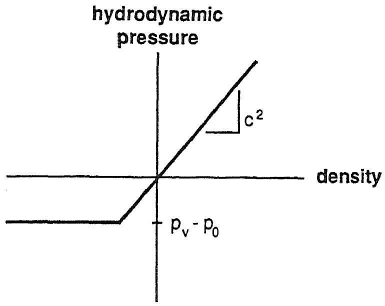



Fig. 1 Bilinear Equation of State for Fluid

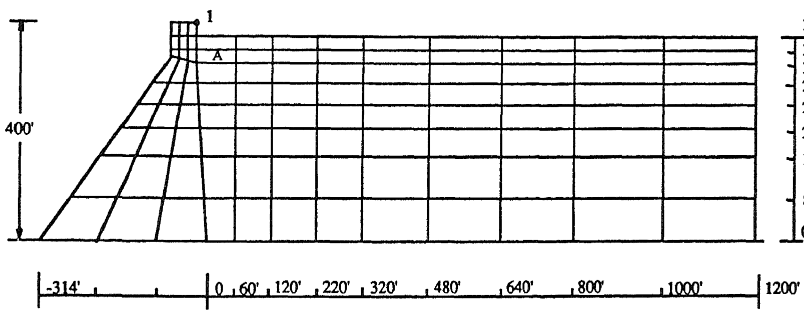
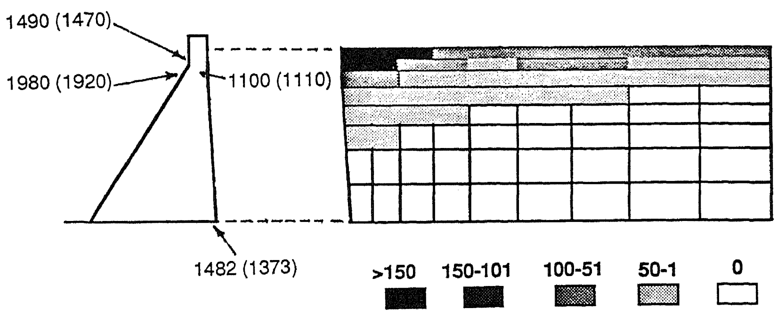



Fig. 2 Finite Element Model of Concrete Gravity Dam-Water System




**a) Maximum Principal Stress in Dam, psi**

**b) Number of Cavitation Events in Water**

Fig. 3 a) Maximum Principal Stresses in Dam Without Cavitation (with Cavitation), and b) Number of Cavitation Events in Water, Due to S69E Component of Taft Ground Motion, Scaled to 1.0 g Peak Acceleration

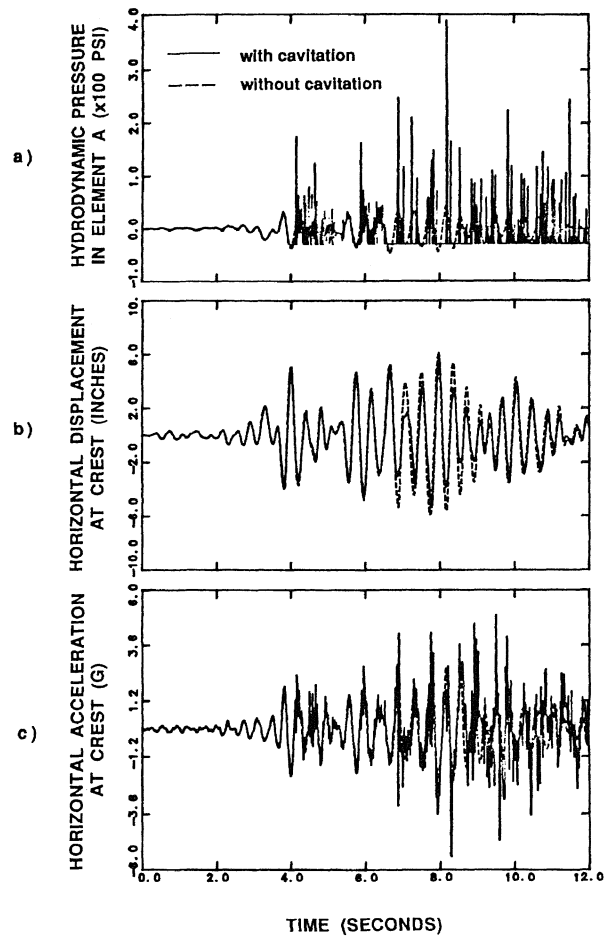



Fig. 4 Effects of Cavitation in Dam-Water System Due to S69E Component of Taft Ground Motion, Scaled to 1.0 g Peak Acceleration

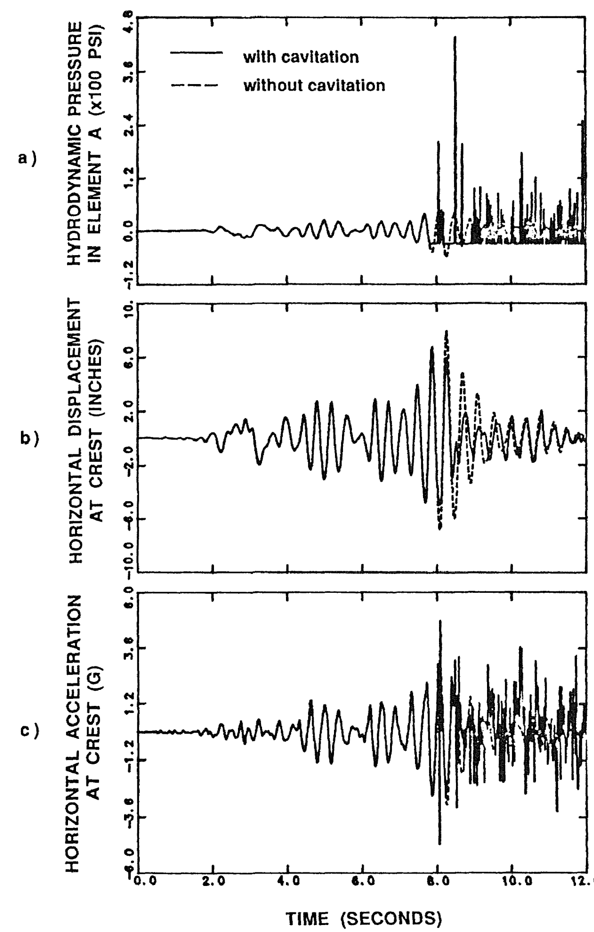



Fig. 5 Effects of Cavitation in Dam-Water System Due to S16E Component of Pacoima Ground Motion